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GIS based multi-criteria assessment of tidal stream power potential: A case study for Georgia, USA

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ABSTRACT

A multi-criteria assessment methodology that accounts for the physical, environmental and socioeconomic constraints is proposed to assist in the selection of the most suitable locations for tidal stream power conversion projects. For this purpose, the tidal stream power resource data are incorporated into a Geographical Information System (GIS) database together with datasets that are related to different aspects of the site selection methodology. The proposed method is applied to the Georgia coast to find and rank the best locations for power conversion. The suitable areas are narrowed down to a subset of the high power density areas that satisfy the constraints of a tidal stream power conversion scheme. A demonstrative ranking procedure with equal weighting factors for all criteria shows that the Savannah, Ogeeche, Canoochee and Medway Rivers and the Cumberland Sound have the best locations for tidal power conversion on the coast of Georgia. This methodology is also applicable to other sites where sufficient geospatial data are available.

Contents

1. Introduction

Given the current and projected global energy demand and the associated impact on the environment, marine energy conversion projects offer viable alternatives with their clean and renewable applications. There are many projects and emerging technologies worldwide to convert the power from the vastly unexploited ocean tides and currents to electric power. Resource mapping is a fundamental step in development of such projects given the distributed nature of these resources. In order to provide this step for any possible future developments in the state of Georgia, the wave power potential and the tidal stream power resource in the region have been investigated [1,2]. The wave power was found to diminish significantly on the broad continental shelf with the regions of larger power being limited to the offshore portion of the shelf. The tidal stream power on the other hand was determined to be substantially amplified at some of the locations along the shoreline, at some specific parts of the Savannah, Canoochee, Ogeeche, Altamaha and Medway Rivers and the Intercoastal Waterway between the

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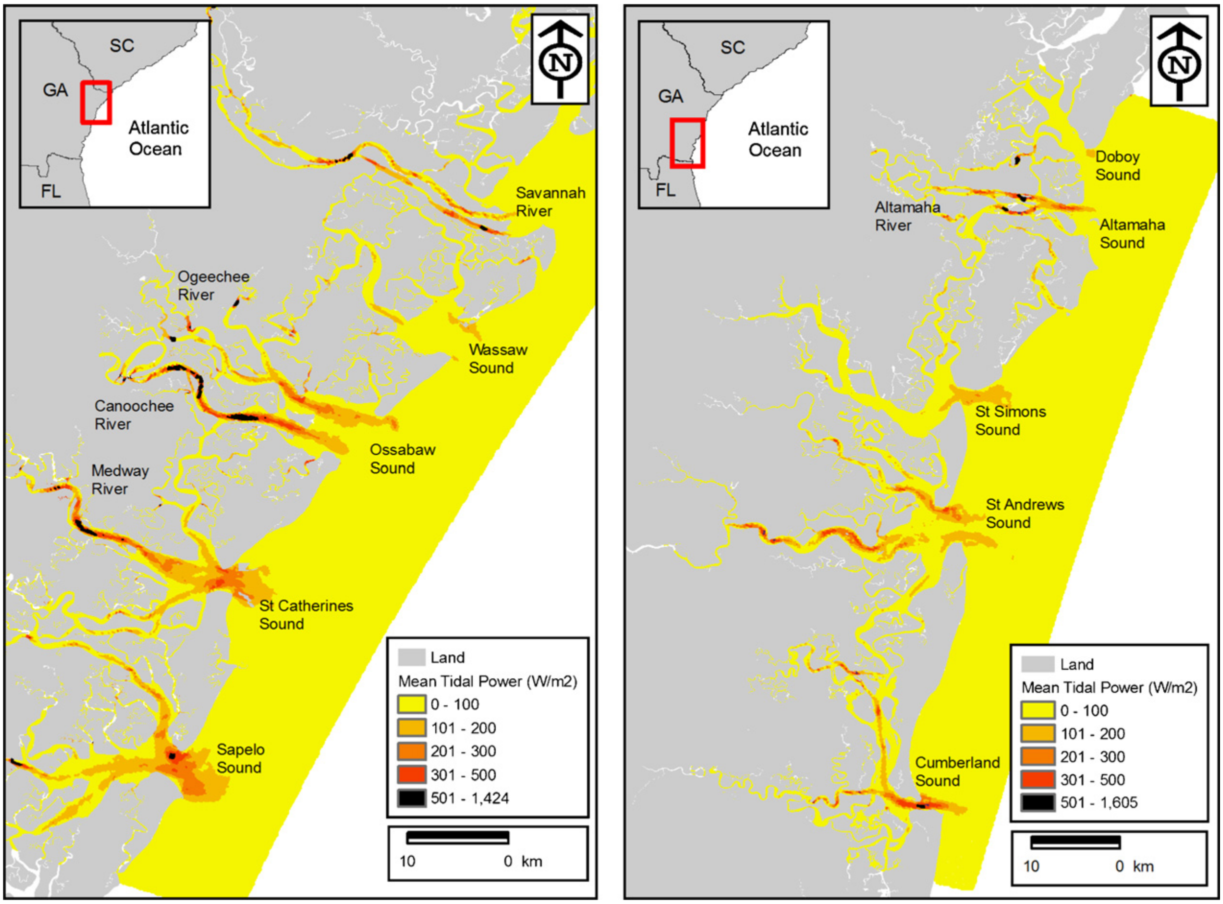

Fig. 1. Mean power density maps along (a) the northern and (b) the southern coasts of Georgia.

Altamaha and the Doboy Sounds as well as St. Catherines, Sapelo, St Andrews, and Cumberland Sounds (Fig. 1). Here, a comprehensive methodology to analyze the tidal stream power potential in the context of the physical, environmental and social constraints using GIS tools has been developed.

This paper is organized as follows: First the factors related to the tidal stream conversion projects are discussed along with the literature on use of GIS as a decision support tool for energy projects. Then, the data coverage, and the methodologies for identification and ranking of the suitable locations are presented in detail followed by the application to the Georgia coast to determine the most promising locations for tidal stream power conversion. Finally, the concluding remarks and suggestions for future work are presented.

2. Literature review

Recently, the International Electrotechnical Commission (IEC) has initiated international standards for marine power conversion systems, TC 114 Marine Energy-Wave and Tidal Energy Converters, which addresses the evaluation and mitigation of environmental impacts, resource assignment requirements, performance measurement of converters and other related issues [3]. Since there is no international standard available at the present, the current study relies upon the methodologies and experiences from other marine renewables and wind power conversion projects.

2.1. Factors related to tidal stream power conversion

The choice of location for a tidal stream power converter farm depends on assessment of a number of criteria including the available power, site characteristics, and environmental, economic and social impacts of the planned project [4–10]. The available power and the site characteristics such as bathymetry, water depth and the geology of the seabed constitute the physical constraints of analysis, which are easier to assess quantitatively than the environmental, economic and social constraints with modeling and measurements.

The environmental impacts can be grouped as the physical impacts, such as changes in the flow patterns and water quality, and related ecological impacts on the aquatic and terrestrial life. The effect on water quality during installation mainly consists of disturbance to the sediment, which results in suspension of sediment and increased turbidity. This is of more concern if the bottom sediment has contamination. During operation, converters alter the tidal energy flow hence the sedimentation patterns and suspension as well as the vertical mixing. Scour and loss of soft sediments might occur near the structures.

In order to avoid the adverse impact on aquatic life, habitats for endangered, protected or sensitive species should be clearly identified and avoided if possible. Because suspension of fine sediment due to construction may have impacts on the immediate surroundings, fish spawning or nursery areas and sensitive benthic habitat should be avoided. While the effect of noise and vibration on aquatic life during operation is a research topic for the ongoing projects, noise and vibration during construction might be more critical especially during breeding, nesting and migration seasons. However, these can be minimized by careful site selection and timing for the project [7]. The mechanical and flow related injuries of the aquatic life from conventional hydropower facilities include impingement with screens and contact with the blades,

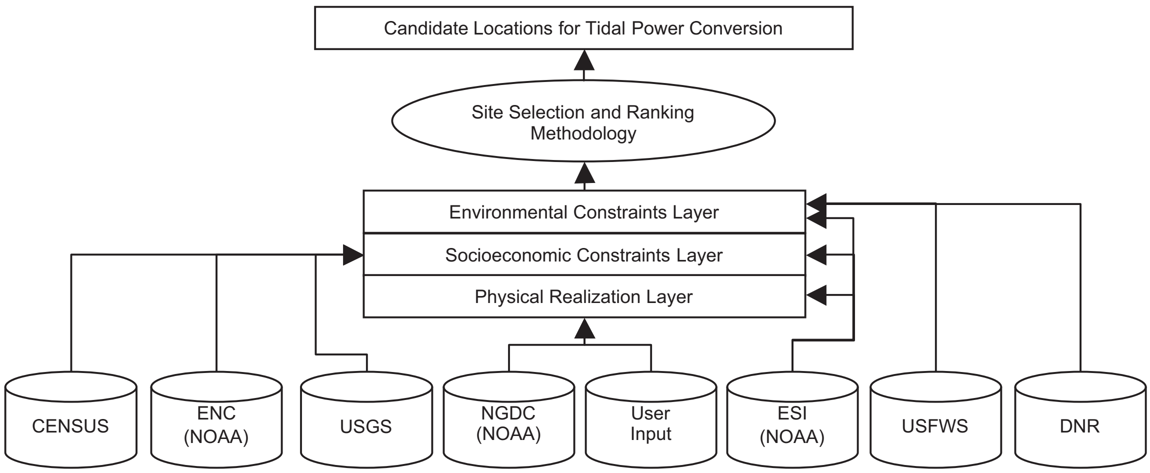

Fig. 2. Structure of geographically referenced information and the underlying data sources used for selecting candidate locations for tidal power conversion.

and abnormal changes in pressure gradients and water velocities. Although converters with unenclosed turbines look similar to boat propellers or hydroelectric power turbines, they operate at much lower speeds and much lower pressures than those traditional devices. The blades are usually slender and the percentage of area swept by the rotor is much smaller. This reduces the probability of fish passing through making contact with the blades. Injury from impingement, abrasion, pinching or grinding is prevented in the absence of a screen of a shroud. The installation stage may also require permanent removal of some terrestrial habitat to construct the shore station, access roads and right of way for the transmission lines [7]. The disturbance to the wetlands should be kept at minimum and temporary as much as possible and permanent changes to the hydrology of the wetlands should be investigated [11].

The economic and social impacts can be evaluated based on the increased energy supply for the region and alterations to the marine and land use. Commercial activities such as shipping and fishing usually share the sea space with recreational and touristic activities. However, during the installation of converters, most of land and marine activities in the vicinity of the project area need to be restricted. At the operation stage, fishing exclusion zones and restricted areas for recreational boats may need to be introduced. If navigation or commercial shipping cannot be avoided, enough safety clearance should be left between the rotor blade and the devices at lowest astronomic tides. The aesthetical concerns and the effects on the cultural and historic sites are additional aspects to be considered when evaluating the environmental effects [5].

Some positive environmental impact may be expected from the converters. Establishing fishing exclusion zones around converters may help increasing the amount of aquatic life by providing shelter for marine life. Project structures, such as transmission cables may serve as suitable structures for invertebrates

Table 1
List of layers, sources and themes and their roles. N.A. indicates the themes that are not assigned any roles.

Layer	Source	Theme	Role
Physical realization	NGDC,	Coastline	Outlines and Filters
	ESI,	Bathymetry	
	NOAA,	Hydrology layer	
	User data	Tidal power map	
Environmental constraints	ESI,	Fish (E)	Critical Areas
	NOAA,	Invertebrates (E)	
	USGS,	Reptiles (E)	
	USFWS,	Birds (E)	
	DNR	Mammals (E)	
		Plants and habitats (E)	
Socioeconomic constraints	CENSUS,	Urbanized areas	Favorable Areas
	USGS,	Transmission	
	DOE,	Transportation	
	DOT,	Built-up areas	
	ENC,	Restricted areas	Restricted Areas
	NOAA	Fairways and shipping lines	
		Dumping sites	
		Cable areas	
		Pipeline areas	
		Shoreline constructions	
		Wreck points	
		Mooring and warping points	
		Recreation areas and access locations	
		(Boat ramps, diving sites, marinas)	
		Management areas	
		(Marine sanctuary, national parks, wildlife refuges, special management areas)	
		Cultural heritage sites	
		(Archeological sites, historical sites)	
		Resource extraction sites	N.A.
		(Aquaculture sites, commercial fisheries, recreational fishing)	

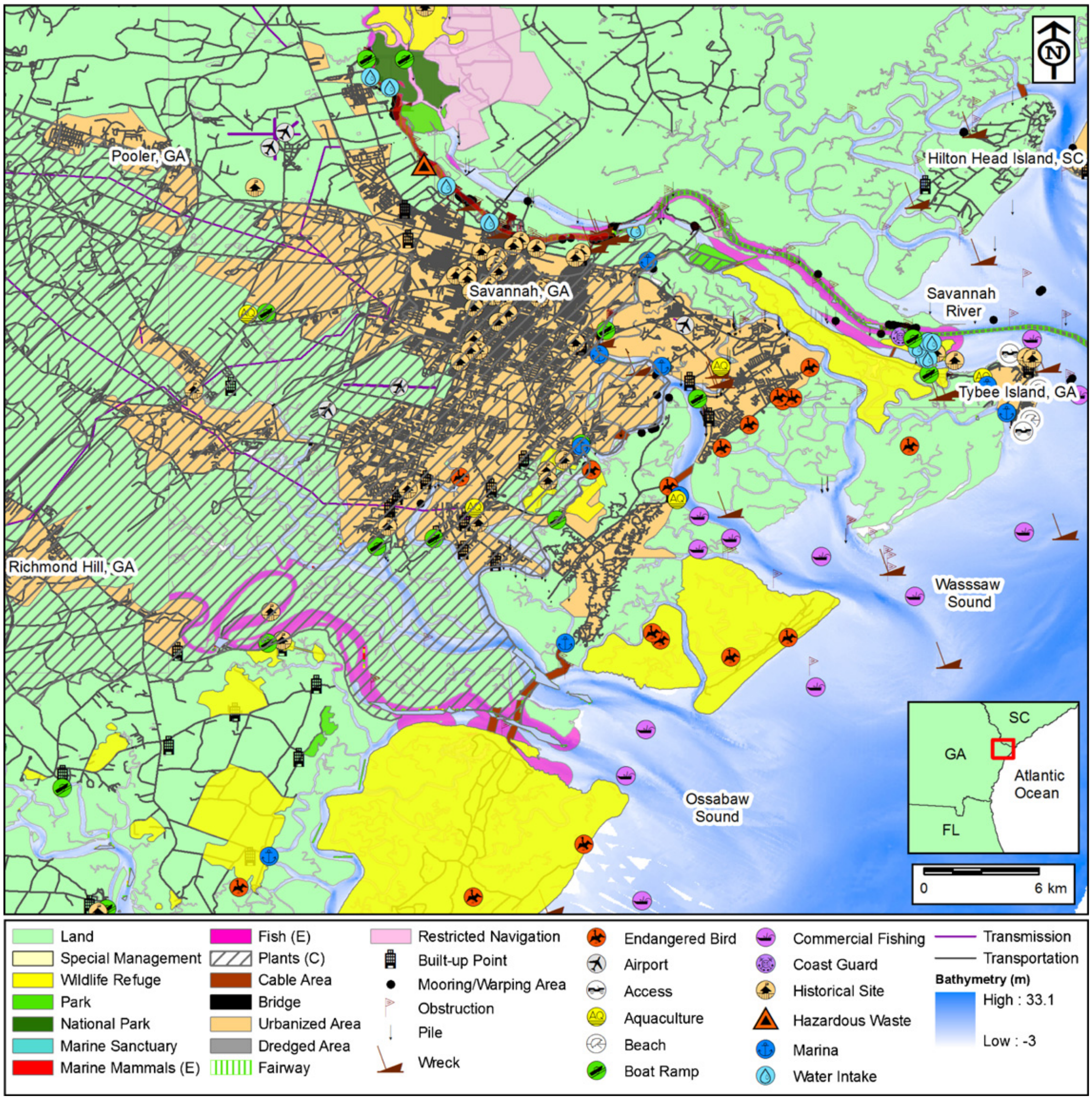

Fig. 3. Demonstration of information from physical, socioeconomic and environmental constraints layers presented on the same map for Savannah River, Wassaw and Ossabaw Sounds.

and macro algae developing an artificial reef for the aquatic community [5].

2.2. Use of GIS in site selection

Although it is not possible to quantify all of these criteria, their evaluation to minimize the consumption of material and energy requires integration of a significant amount of information, which makes utilizing GIS tools extremely beneficial [12]. For the last 20 years GIS applications have been successfully used to assess environmental and economic constraints, and to select suitable sites for energy projects [13–30]. The suitability of GIS to serve for this purpose was proposed earlier [12], while its performance and shortcomings having been evaluated more recently [31]. A decision support system to site wind power conversion projects was first defined in 1980 [23]. The system involved resource analysis, quantifying the proximities to areas of interest or special importance and excluding the restricted areas. The results were ranked and synthesized in a matrix in order to identify the most suitable locations. Through the years there has not been significant change in the methodology and in 2000, a GIS-based approach with a similar methodology was used to evaluate sites for wind farms in the UK [15]. Although there are significant differences between them [9,32,33], the essentials of wind power and tidal stream power conversion are close enough that a similar workflow can be created to assess the suitability of locations for tidal stream power conversion projects. Recently, more comprehensive approaches became available, such as the marine resource assessment of the UK [34] and the Ocean Special Area Management Plan in the state of Rhode Island [35], which can provide guidelines for future studies. There are no set rules on how to determine acceptable limits for changes to the currents and sediment transport climates caused by current energy extraction devices. Reports on assessing the tidal power potential of North America focusing on a few specific regions with high potential to identify the environmental impacts and economic constraints and assess the available technologies for suitability, and other related studies can be used as a guide for determining the related factors [8,36,37].

3. Methodology

This section describes how the various data and constraints are incorporated into a decision making tool to assist in the site selection. First, the data from various sources are compiled in a GIS

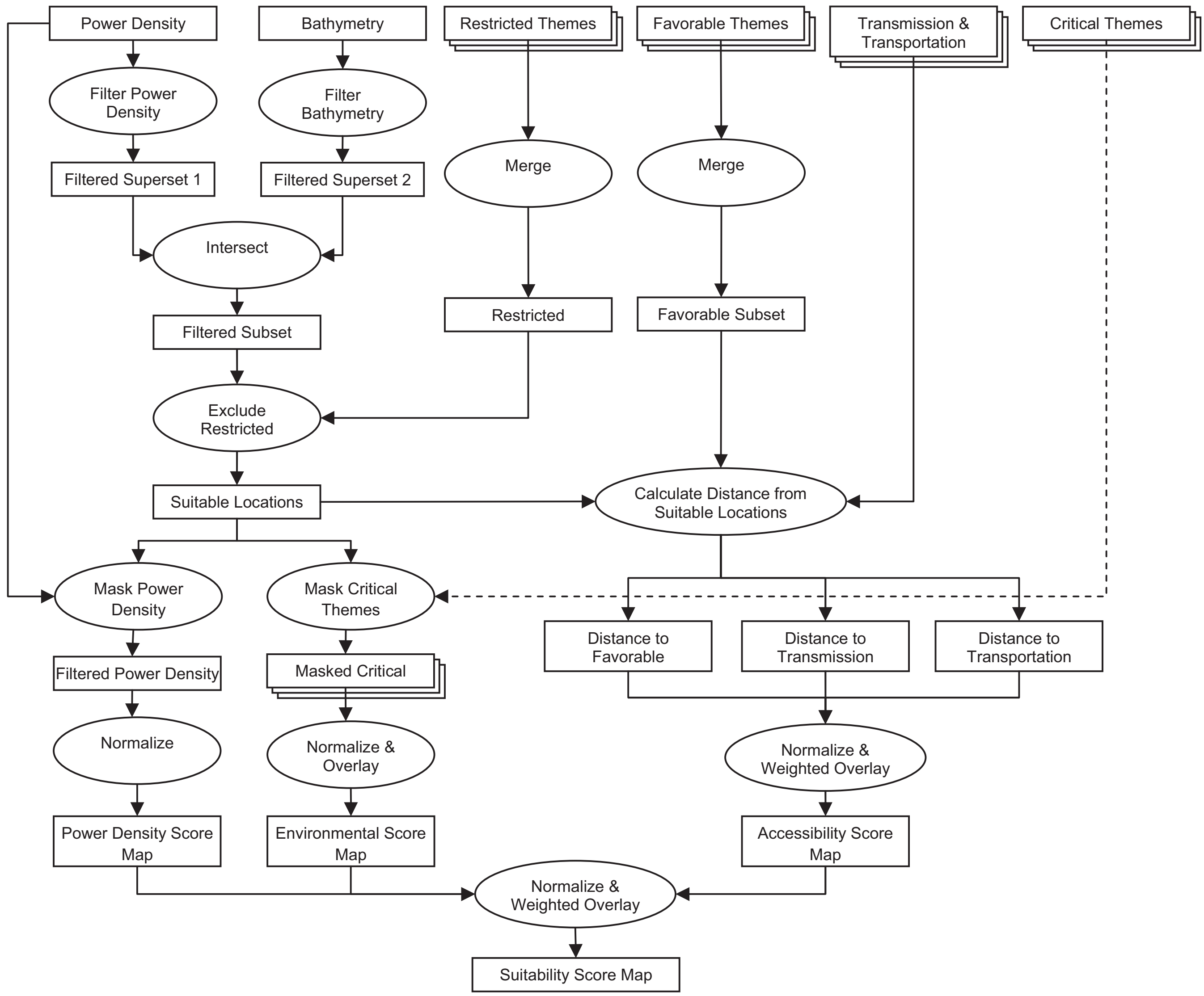

Fig. 4. Flow diagram of the site selection methodology for tidal power conversion. Ovals represent actions and rectangles represent objects.

environment and the themes in each dataset are classified into conceptual layers. Then, map regions are identified according to the role of each theme in tidal stream power conversion. Finally, the suitable locations are determined and the ranking algorithm is applied to calculate the score for each location and determine the best areas for tidal stream power project siting. The data coverage, definition of conceptual layers, and the details of the identification and ranking algorithms are discussed in details within this section.

3.1. Data coverage and classification

A large amount of GIS data is available online, scattered between governmental offices, science centers and the private sector, which requires significant amount of work to compile. The GIS portals such as the Georgia GIS Data Clearing House [38] and the Geodata [39] facilitate the retrieval of state wide and country wide geographic data, respectively. However, the data origins still vary, resulting in different datums, projections, scales and resolutions. Some of the data may be formatted to be used with specific software packages and on specific platforms. Hence, the attached metadata needs to be examined for compatibility and conversion between the datasets. After an extensive investigation of online resources, the number of related sources is reduced down to a set of major data providers according to their coverage of information, data quality and accessibility. These major sources include National Oceanic and Atmospheric Administration (NOAA) through Electronic Navigational Charts (ENC), National Geophysical Data Center (NGDC) and Environmental Sensitivity Index Maps (ESI); and United States Geological Survey (USGS), United States Census Bureau (CENSUS), and Environmental Protection Agency (EPA). State and local environmental information can also be accessed at Georgia Department of Natural Resources (DNR) and U.S. Fish & Wildlife Service (USFWS).

The geospatial data gathered from various sources are categorized into three conceptual layers: The physical realization layer, the environmental constraints layer and the socioeconomic constraints layer (Fig. 2). These layers include the information on the basic geometry and physics of the problem, areas that are of environmental concern, and areas of social and economic concern, respectively.

3.1.1. Physical realization layer

The physical layer consists of the 1/70,000 scale, medium resolution shoreline from NOAA, the digital sounding data from NGDC as the bathymetry and the tidal stream power density map. This layer, defining the physical boundaries and the amount of kinetic power per unit cross-sectional area, contains the most essential

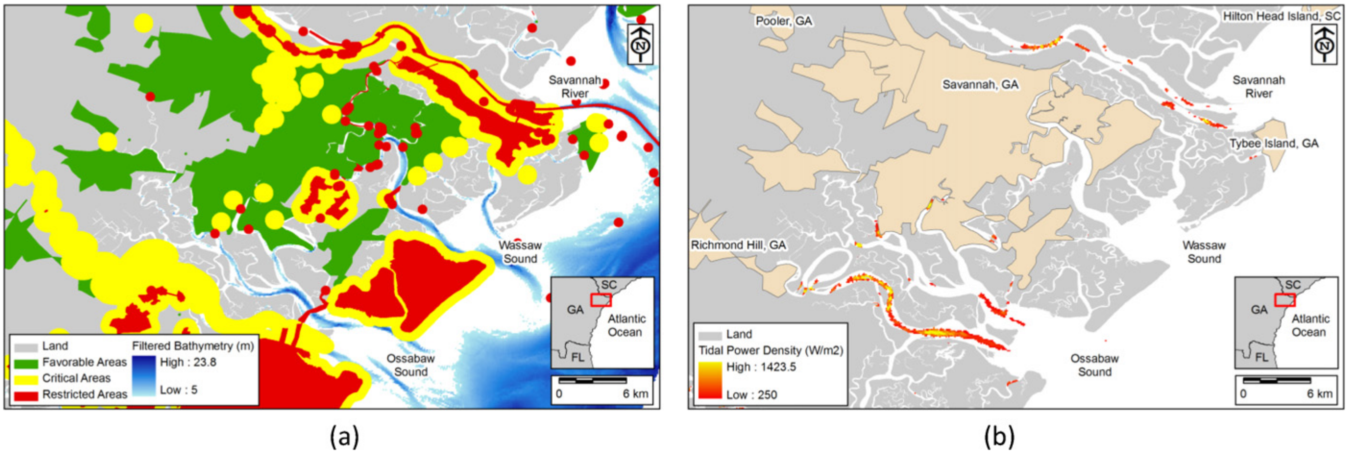

Fig. 5. (a) All exclusive (red), critical (yellow), and favorable (green) areas for tidal stream power conversion in Savannah River, Wassaw and Ossabaw Sounds. Bathymetry filtered by a minimum depth of 5 m. (b) Tidal power density filtered by a minimum of 250 W/m^2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

data for the site selection scheme. One of the important factors is the depth of flow, which is used to verify the necessary vertical space to allocate the tidal power converters. Despite including the essential data, the physical layer itself alone is not sufficient to perform a rigorous multi-criteria assessment.

3.1.2. Environmental constraints layer

All plants, animals and microorganisms and the non-living physical factors of an environment is called the ecosystem of that area. Tidal stream power converters with their slow motion which may be avoided easily by fish and other sea animals [5] and low noise levels are expected to have low impact on the ecosystem of an area. Nevertheless, it is still necessary to evaluate their possible interference with the ecosystem further, especially where endangered species are present. This study does not attempt to answer these questions, but only use the related findings available in the literature. Environmental considerations require mapping of the endangered species habitats and avoiding these locations wherever possible. Although they are mainly prepared for oil and chemical spill response purposes, ESI maps provide some essential data such as sensitive biological resources and seabird colonies that can be used in the site selection methodology [40]. Detailed information on the threatened and endangered species in Georgia can also be obtained from USFWS Endangered Species and Georgia Ecological Services [41,42]. The GIS data from this source is merged with ESI data for the environmental constraints layer. Supplementary data are provided from Georgia Environmental Resources Digital Data Atlas, which is served by USGS Center for Spatial Analysis Technologies [43].

3.1.3. Socioeconomic constraints layer

The socioeconomic constraints layer contains the related human activities in the region. ENCs provided to the public by NOAA's Office of Coast Survey are vector-based digital files containing marine features suitable for marine navigation and GIS applications and usually used for route planning [44]. They carry information on the manmade structures and marine activities. The census data provides information about built-up areas classified by their surface area and the size of inhabiting population. Some of the supplemental data such as transportation and transmission lines can be found in Georgia Environmental Resources Digital Data Atlas. The location and orientation of transmission lines and the roads are some of the important factors for power conversion projects. ESI maps also provide some socioeconomic information which includes but not limited to location of boat ramps, historical sites, and aquaculture and fishing sites. Sensitive human-use resources, such as water intakes, marinas, and swimming beaches are also marked in ESI maps.

3.2. Identification of map regions

The suitable areas are determined based on the level of power density, ease of accessibility and the number of environmental conflicts with the site selection methodology. For this purpose, each theme is tagged according to its role in the tidal stream power conversion. The list of themes, their roles, sources and the layers that they belong to are presented in Table 1. The themes in the physical realization layers are used to set the physical constraints and boundaries of the problem and are tagged "outlines and filters". The themes with sensitive biological resources data are tagged as "critical", whereas the themes where it is socioeconomically more advantageous to have the power conversion projects closer are tagged as "favorable" and the themes where the placement of a tidal power converter would not be allowed or should be avoided are tagged as "restricted". An example of most of the data themes excluding the tidal power density data are shown on a coastline section that includes a part of Savannah River, Wassaw and Ossabaw Sounds in Fig. 3. The definition and classification of each theme is discussed in the following paragraphs.

The critical areas include the habitats of endangered species, which are at risk of becoming extinct. Endangered species are usually under legal protection and human activities in the proximity of their habitat are limited. Therefore, the list of the sensitive biological resources acquired from the GIS database is filtered to include only the species that are listed as endangered on the state or federal lists of endangered species. This is denoted by appending the theme name is appended with "(E)" in Fig. 3 and Table 1. The endangered marine mammals along the Georgia coast include whales and manatees. Given their size and offshore habitats, the whales are not as common as manatees in shallow estuaries and tidal creeks of the Georgia coast. High-use areas for the endangered West Indian Manatee species are Cumberland, St. Andrews, and St. Simons Sounds on the south and Savannah River on the north (Figs. 1 and 3). The official state marine mammal of Georgia, the Northern Right Whale, is known to prefer areas offshore of Cumberland, St. Andrews, and St. Simons Sounds for breeding. The second-largest living animal and an endangered species, the Fin Whale, can be found at offshore of Georgia (Gray's Reef National Marine Sanctuary) at certain times of year. Reptiles (E) and Fish (E) in Georgia include the Green Sea Turtle and the Shortnose Sturgeon, respectively. The Shortnose Sturgeon

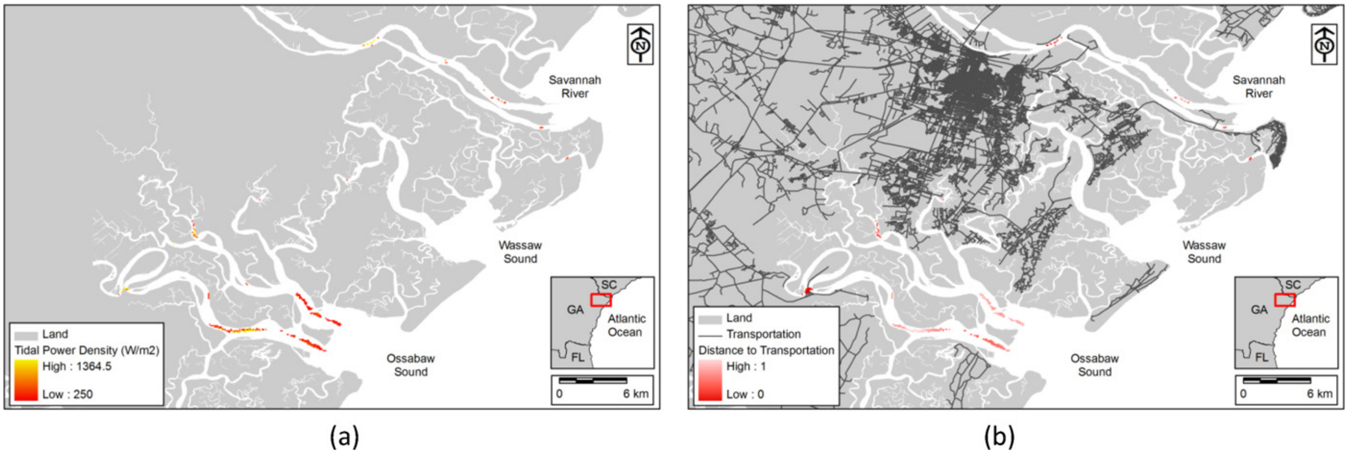

Fig. 6. (a) Tidal power density in the Savannah River, Wassaw and Ossabaw Sounds filtered by a minimum of 250 W/m^2, 5 m depth and with restricted areas removed. (b) Normalized distance to transportation lines from the suitable locations for tidal stream power conversion.

inhabits Savannah, Canoochee, and Altamaha Rivers, whereas the Green Sea Turtle is observed mostly at Gray's Reef. The endangered bird species in the coastal Georgia are limited to Wood Stork, which have their nests scattered across the coastal zone (Fig. 3). Although Bald Eagles are listed as endangered in ESI maps, they were reclassified from endangered to threatened in 1995 by USFWS, and were removed from the USA federal government's list of endangered species in 2007 [45]. Threatened species such as Frost Flatwoods Salamander and Indigo Snake or the plants classified as Species of Concern (C) such as Pondspice are not considered to be critical since they are not a part of endangered species [41].

Power from converters is anticipated to promote the local activities and developments in the coastal zone; therefore, socioeconomic considerations favor the locations that are closer to the socially developed areas, such as urbanized and built-up areas, where most of the demand is located. An urbanized area is defined as a densely settled territory that contains 50,000 or more people [46]. The extent of the urbanized areas is based on the CENSUS 2000 data (Fig. 3). Built-up locations are defined as a concentration of buildings supporting road or rail infrastructure [47]. Airports and U.S. Coast Guard facilities are considered as parts of built-up areas. Electric power transmission and all ground transportation are, respectively, indicated as transmission lines and transportation lines in Fig. 3. The right of way for the transmission lines and for the roads to access the selected area is another important decision factor. The right of way represents a big part of the cost of construction and it may also disturb the immediate nature and habitat [5]. It is desired to keep the right of way for the transmission and the access roads as short as possible. Therefore, the proximity of the power conversion projects to the main power grid for connection and to the transportation grid for easy access is also advantageous.

The restricted areas need to be excluded from tidal power conversion projects, due to their potential impact on the environment and on the existing use of sea space. The areas managed by the USFWS as National Wildlife Refuges or by Georgia DNR as State Wildlife Management Areas are shown as Wildlife Refuge in Fig. 3. National parks include national parks, seashores and monuments managed by the National Park Service. Marine sanctuaries denote the areas managed by the NOAA Sanctuary and Reserves Division as National Marine Sanctuaries and as National Estuarine Research Services by NOAA and the state. These areas and together with areas designated by an appropriate authority within which navigation is restricted in accordance with certain specified conditions are marked as possible exclusive areas for tidal stream power conversion projects. Fairway is defined as a part of a river where the main navigable channel for vessels of larger size lies i.e. shipping channel, a mooring/warping facility is the structure used to secure a vessel, and a dumping site is a sea area where dredged material or other potentially more harmful material is deliberately deposited [47]. Pipeline areas consist of a string of interconnected submarine or overhead pipes used for transport of matter such as oil or gas. All fairways, dredged areas, mooring/warping facilities, dumping sites, historical sites and pipeline areas are considered as parts of the restricted areas. Recreation areas including boat ramps, diving sites and marinas are also considered as restricted.

General areas where commercial fishing activities take place are marked with specific symbols in Fig. 3. Recreational fishing is abundant along the Georgia coast, hence omitted. Locations for farming of freshwater and saltwater organisms are marked as aquaculture sites on the map. Some of these locations of interests such as aquaculture, commercial fishing, are not included in the site selection methodology at this stage. The benefits and the impact of tidal power conversion on these require special feasibility and design studies, and should include discussions and communications with all of the interested parties. Similarly, piles, obstructions, beaches, access locations and water intakes are not considered as factors for site selection.

A flow diagram that shows the steps in the implementation of the site selection methodology is provided in Fig. 4. Regardless of their design, most of the tidal stream power converters have a minimum depth requirement based on their dimensions. Additionally,

Table 2
Ranking results for tidal power conversion along the Georgia coast at selected locations shown in Figs. 7 and 8.

Point	Lon	Lat	Power density score (P)	Environmental score (E)	Accessibility score (A)	Overall suitability score (S)	Rank
A	−81.029	32.087	0.5	0.7	0.8	0.53	2
B	−81.127	31.857	0.6	0.3	0.5	0.30	5
C	−81.265	31.755	0.5	1.0	0.6	0.63	1
D	−81.182	31.539	0.2	1.0	0.5	0.36	4
E	−81.344	31.327	0.6	0.0	0.4	0.10	6
F	−81.448	30.708	0.4	0.7	0.8	0.50	3

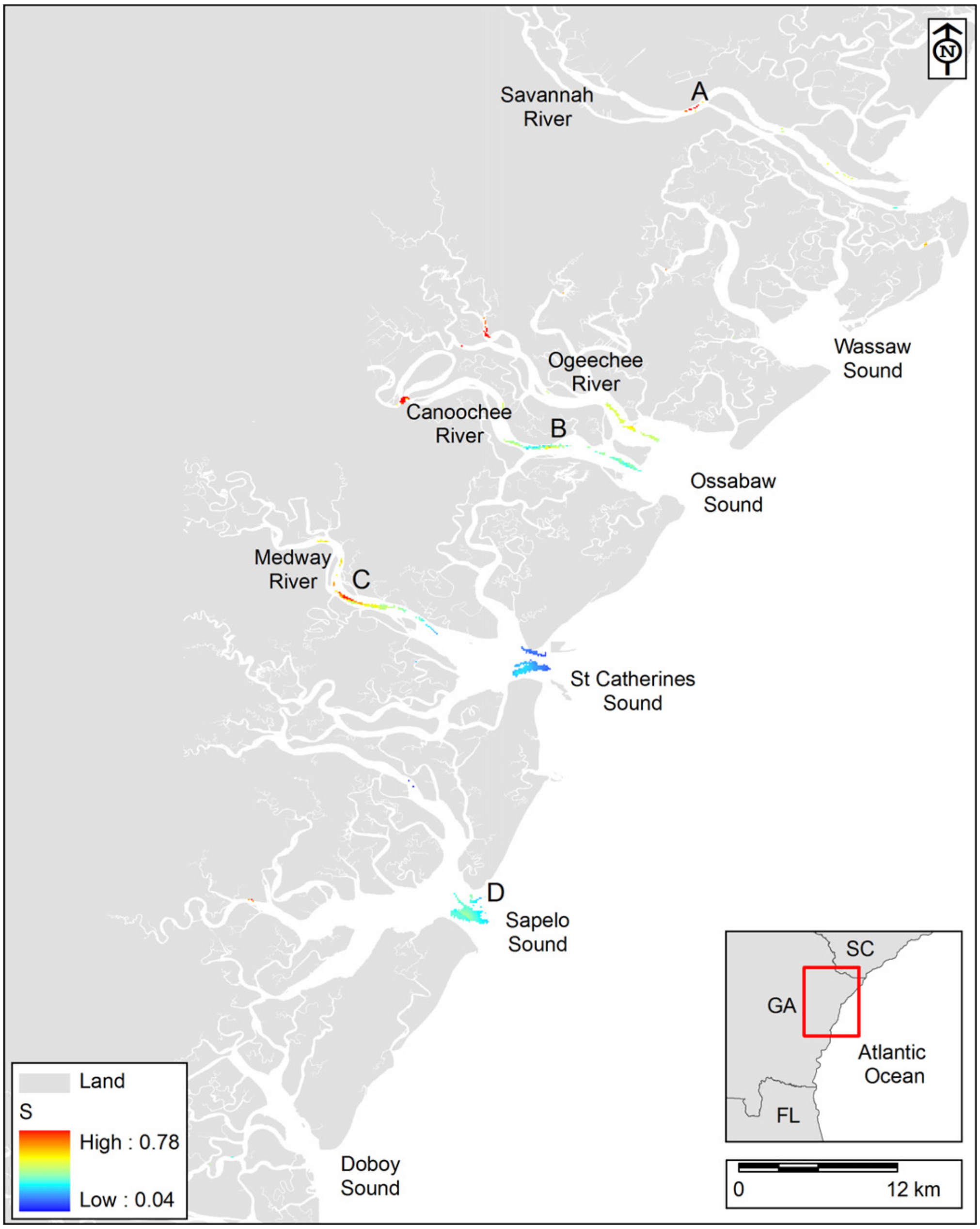

Fig. 7. Candidate locations with tidal power conversion potential on the northern Georgia coast that are determined by applying the site selection methodology.

there is usually a minimum flow speed (i.e. cut-in speed) that is required for the devices to start extracting power from the flow. The geospatial data for the power density and the bathymetry are filtered by minimum values to get the maps for filtered supersets (Fig. 4, top left). The intersection of these two supersets gives the filtered subset. The themes with restricted areas are merged into a single theme called restricted after applying certain buffer areas around the features (Fig. 4, top middle) and then excluded from filtered subset to determine the suitable locations. Similarly, the themes that contain the favorable locations are also merged into a single polygon. The habitats of endangered species are extracted from the GIS database and specific buffer zones are applied around them based on the federal and state regulations. The map of suitable locations is used to mask the power density and the critical areas maps, in order to calculate the scores for these locations. Likewise, the distances to favorable areas and transmission and transportation lines from the suitable locations are computed to facilitate the calculation of the accessibility scores. Finally, these scores are normalized and overlaid on the map to determine the candidate locations for tidal power density conversion. For normalizing each map, the maximum score in that map is used so that the data values range between 0 and 1, 1 being the best score.

3.3. *Ranking of suitable locations*

The site selection methodology can serve as a useful preliminary analysis tool for decision makers before allocating resources for a more detailed evaluation. Consequently, the criteria for ranking the candidate sites can be simplified to three essential scores related to the level of power density, accessibility of the site, and the environmental challenges.

Normalized power density and the normalized environmental constraint are used to define two of the scores, whereas the normalized distances are combined into a single term to define the

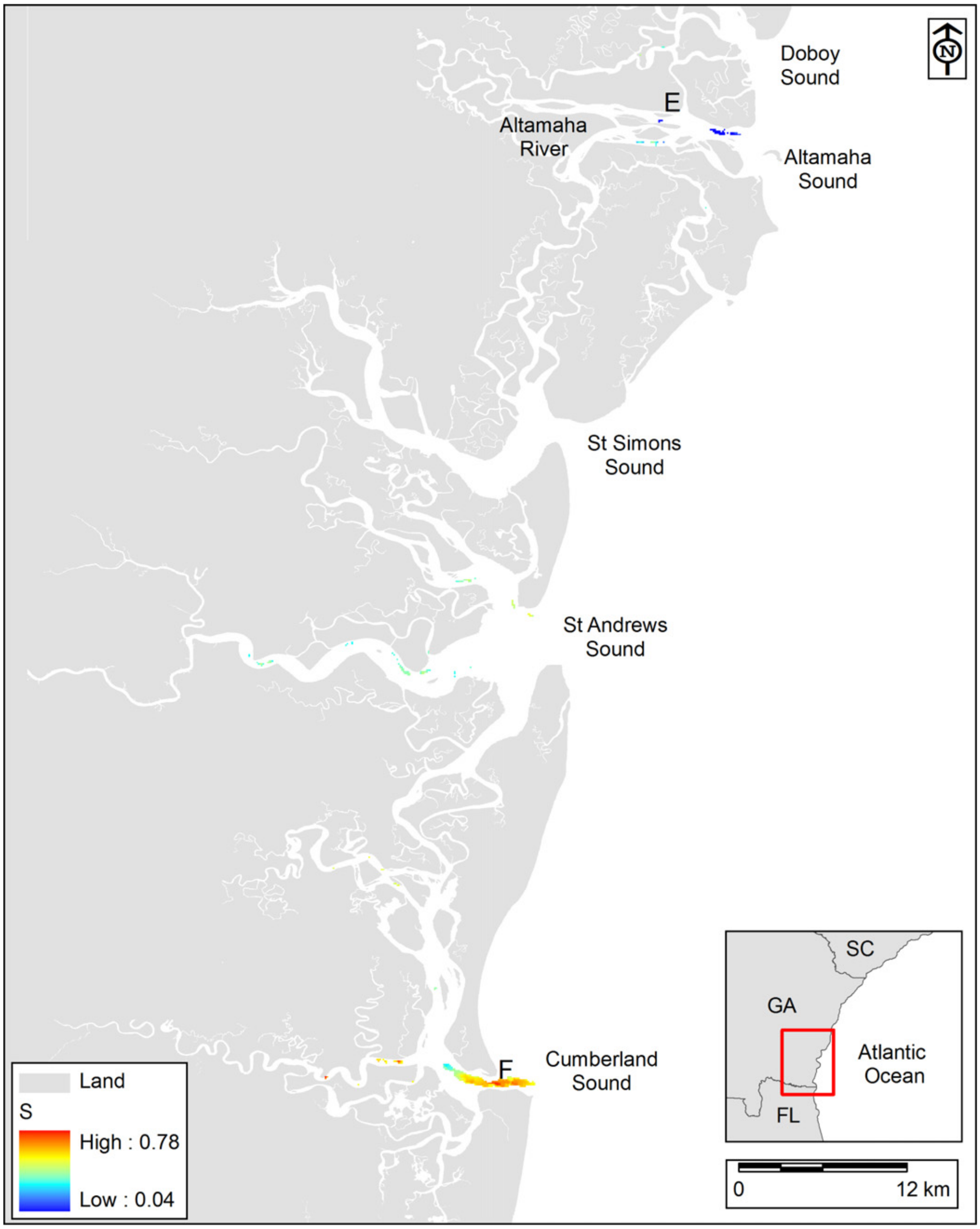

Fig. 8. Candidate locations with tidal power conversion potential on the southern Georgia coast that are determined by applying the site selection methodology.

accessibility score. It is important to note that the accessibility score is related to economics, but it is not used in the ranking algorithm here since an economic analysis is beyond the scope of this study.

The power density for every point is normalized with the maximum power density in the potential areas using

$$P = \frac{PD}{PD_{\max}} \tag{1}$$

where P is the power density score, PD is the power density at a point and $PD_{\max}$ is the maximum power density within the suitable areas (i.e. Filtered Power Density in Fig. 4), so that the point with the highest power density scores 1.

Each distinct conflict with the environmentally sensitive locations on the filtered critical areas map is itemized and the values on the map are normalized with the total number of possible conflicts using

$$E = 1 - \frac{NE}{NE_{\max}} \tag{2}$$

where E is the environmental score, NE is the number of conflicts at a point and $NE_{\max}$ is the maximum number of conflicts. For example if the maximum possible number of conflicts is 4, a point in the buffer zone for the endangered bird species gets 0.75, whereas another point that lies on the intersection of the buffer zone of the endangered bird species and endangered fish gets 0.5. The point that has all possible conflicts gets a score of 0.

The distances to transportation and transmission lines and to favorable areas from every point on the suitable areas are computed and normalized so that the closest point to the transmission lines gets a score of 1 and the most distant location gets 0. The normalized

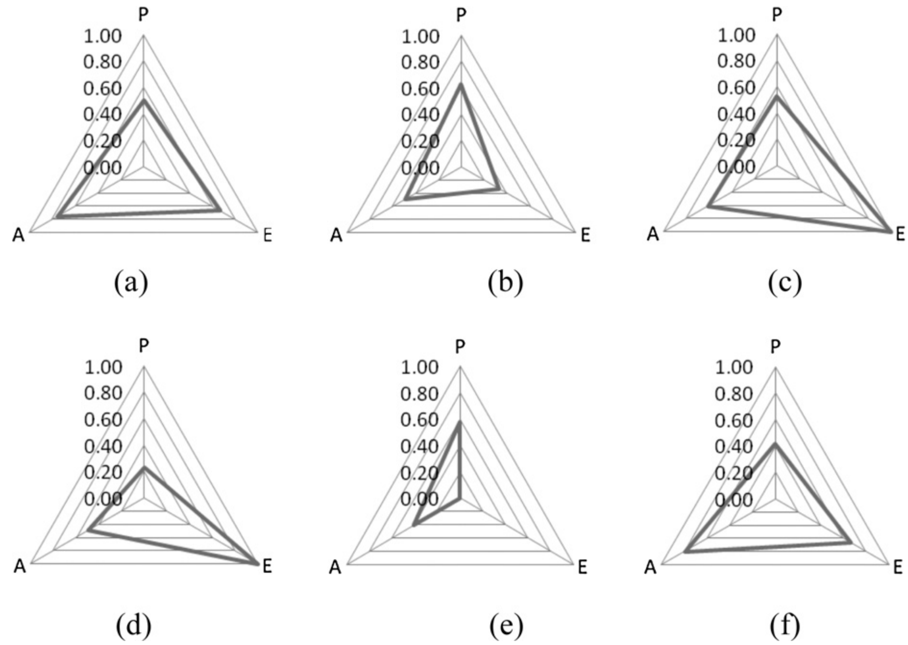

Fig. 9. The power density (P), accessibility (A) and environmental (E) scores of tidal power conversion along the Georgia coast at selected locations shown in Figs. 7 and 8.

values are combined to get the accessibility score by

$$A = 1 - \left(\frac{k_m}{k_m + k_p + k_f} \cdot \frac{DTM}{DTM_{\max}} + \frac{k_p}{k_m + k_p + k_f} \cdot \frac{DTP}{DTP_{\max}} + \frac{k_p}{k_m + k_p + k_f} \cdot \frac{DTF}{DTF_{\max}} \right) \quad (3)$$

where A is the accessibility score, DTM, DTP and DTF are distances to transmission and transportation lines and favorable areas, respectively. The terms k_m, k_p and k_f are weighting coefficients, which are assumed to be equal in this study. Finally, the three scores are used to generate a triangular Kiviat diagram (radar chart). The quality of each location for tidal power conversion is computed from the area under the triangle using the formula

$$S = \frac{k_p \cdot P \cdot k_a \cdot A + k_p \cdot P \cdot k_e \cdot E + k_a \cdot A \cdot k_e \cdot E}{k_p \cdot k_a + k_p \cdot k_e + k_a \cdot k_e} \quad (4)$$

where k_p, k_a and k_e are the weighting coefficients for P, A and E, respectively. S is the overall suitability score nondimensionalized by the maximum possible area. A triangle with a larger area corresponds to a higher overall suitability score, hence a higher rank. In this study, power density, accessibility and environmental scores are assumed to have equal weights and the nondimensional suitability score is calculated by

$$S = \frac{P \cdot A + P \cdot E + A \cdot E}{3} \quad (5)$$

4. Site selection methodology applied to Georgia coast

The methodology is applied to the entire Georgia coast; however, intermediate steps are illustrated on a smaller section of the coastline, which consists of the Savannah River, Ossabaw and Wassaw Sounds (Figs. 5 and 6). All merged favorable, restricted and critical areas are shown in green, red and yellow, respectively, in Fig. 5a, where the circles with various sizes indicate the buffers created around the locations of interest. The size of the buffer is based on the related regulations whenever information is available, or a reasonable distance is determined based on the satellite imagery. All boat ramps, mooring/warping locations, marinas and coastguard are marked with a 400 m buffer. The locations indicated as hazardous in the original are applied 800 m buffer. Restricted navigation, pipelines, dumping ground, fairway, dredged area, cable locations and the special management areas are already defined as polygons in the original datasets and no buffer is required for these areas. Similarly, the urbanized area polygons are used as is, whereas all airports and built-up locations have a 100 m buffer. The spatial distribution of the endangered species other than the Wood Storks is provided as polygons in the original datasets and is used as is for the site selection methodology. Based on the environmental regulations the nest locations have a buffer zone of 800 m [41,42]. Correspondingly, the same distance is used for creating buffer zones around boundaries of the special management areas, such as wildlife refuges and national parks.

There is no standard for the size of power conversion devices, and most of the existing devices and prototypes are built to meet the requirements of a certain project with the dimensions of the devices changing from several meters to tens of meters [48,49]. Since the analysis in this study does not depend on a specific device and given the limited depth in Georgia coastal waters; the minimum depth is chosen to be 5 m, large enough to accommodate a small size conversion device with the existing technology. The bathymetry filtered by 5 m for the Savannah River, Wassaw and Ossabaw Sounds is shown as an example in Fig. 5a. It is seen in this figure that the 5 m filter already removes a substantial amount of area from the whole domain, leaving only limited areas along the main rivers and part of the sound entrances.

The cut-in speeds for the tidal power conversion devices range from 0.5 m/s to 1 m/s depending on their design. Although some studies that simulate power extraction acknowledge cut-in speed values for the horizontal axis turbines as large as 1 m/s [50,51], there are many examples with cut-in speeds around 0.7 m/s and a vertical axis turbine with 0.5 m/s [49,52,53]. The minimum for the power density is selected as 250 W/m^2 which corresponds to a flow speed of 0.8 m/s. The example of the filtered power density for the pilot area is shown in Fig. 5b. The larger power density is constricted to the rivers and river mouths for this example. When the restricted areas are excluded from the subset of locations filtered for depth and the power density, the potential areas for tidal power conversion reduce drastically (Fig. 6a). The normalized distance to transportation lines from the suitable areas for the pilot region is

shown in Fig. 6b as an example, demonstrating that a location with larger power may not have ease of access, which is likely to add up to the cost of a project.

The suitability score maps for the north and the south sections of the coast are shown in Figs. 7 and 8, respectively, after all normalized maps are overlaid on the entire Georgia coast. Based on the power density score map, St. Catherines, Sapelo and Cumberland Sound entrances and the Ogeechee, Canoochee and Altamaha River mouths are found to have large areas of candidate sites for power conversion, with the Cumberland Sound having the largest power density amongst all. The Canooche and Medway rivers have considerably higher power density over a substantially large area that meets the criteria, and there are few isolated patches of very small areas such as Savannah River and upstream Altamaha River. It is seen in Figs. 7 and 8 that some of the areas with large power density presented in Fig. 1 are eliminated, and a more useful subset of suitable areas is obtained when the methodology developed here is applied to the Georgia coast. The maximum suitability score is found to be 0.78, which is less than 1, meaning that none of the suitable locations is perfect in meeting all of the criteria. The locations with the highest suitability scores are discovered in the Savannah, Ogeechee, Canoochee, Medway Rivers and the Cumberland Sound considering equal weights for each criterion.

Six locations that have larger power density relative to their surrounding area are selected from the candidate areas to demonstrate the use of site selection methodology as a decision support tool. Labeled A to F from North to South, respectively, these locations are in the Savannah, Canoochee, and Medway Rivers, Sapelo Sound, Altamaha River and Cumberland Sound. The ranking scores for these locations are shown on Kiviat diagrams in Fig. 9 and the results are summarized in Table 2. Based on the ranking algorithm, Location E is ranked the worst of the six locations, since it has a conflict with all possible critical areas, and has low accessibility. Location B is also one of the environmentally disadvantageous locations, although it has a moderate power density. Location D and F are more preferable than locations B and E. Location D has no environmental conflict, but considerably less power than all other locations while location F is more accessible and has a larger power density, but not as environmentally friendly as location D. Therefore, ranking between these two locations requires a more detailed analysis. On the other hand, location A has larger power density than location D, and ranks better than D and F. The accessibility of location C is not the highest of all, which means the cost related to access roads and connection to the grid is expected to be higher. However, it has a substantial tidal power density and no environmental conflict. Therefore, location C gets the highest rank based on the implemented algorithm.

5. Conclusions

A set of parameters that are necessary to evaluate suitability and classify the favorability of a site for power conversion is established based on the analogy from site selection practices from other marine renewables, hydropower and wind energy projects. A methodology for selecting suitable sites for tidal power conversion is developed, and implemented using the available geospatial data and relevant GIS tools. It is applied to the Georgia coast to distinguish the areas with higher tidal power that meet the requirements of the multi-criteria selection methodology. The suitable sites for tidal power conversion are marked and evaluated for quality based on three essential criteria; the level of power density, the accessibility of the site and the number of environmental conflicts. There are relatively strong local currents within the complex network of tidal rivers and inlets between barrier islands along the Georgia coast [1]. It is shown that the depth constraints, human activates in the coastal zone and the sensitive biological resources limit the amount of suitable location for tidal power conversion once the site selection methodology is applied. Assuming equal weights on each criterion, it was found that parts of the Savannah, Ogeechee, Canoochee and Medway Rivers and the Cumberland Sound proved to be the most promising locations.

Field measurements that are long enough to extract the tidal constituents are still required to validate the tidal stream power density at the selected locations. The design of tidal power conversion devices is a developing research area and the suitability of the various available technologies should be investigated for extracting tidal power on the Georgia coast. Since the economic factors such as the cost and energy output depends on the type of the device it is not addressed in this study. Nevertheless, the developed methodology can be applied to other locations on the USA coast with small modifications. If there is sufficient geospatial data, it can also be extended for coastal zones on other parts of the world.

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